Significance of glaciers, rockglaciers and ice-rich permafrost in the Northern Tien Shan as water towers under climate change conditions

Bolch, Tobias ; Marchenko, Sergei

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Tobias Bolch, Sergei Marchenko

Trend analyses for the period from 1879 to 2000 at 16 climate stations located in and around Northern Tien Shan show an air temperature increase, which has become pronounced since the 1950s. This can be attributed mainly to a temperature rise in autumn and winter. However, the increase is less pronounced in the mountainous areas. For precipitation, there was a small increase on average, but no clear trend. Geothermal observations during 1974–1977 and 1990–2006 indicate that the permafrost has also been warming in the Tien Shan Mountains during the last 30 years. On average, the decrease was more than 32 ± 8 % in glacier extent and about 37.5 ± 9 % of glacier volume between 1955 and 1999 in the investigated six valleys. In 1999, active rockglaciers covered ca. 13 % of the glaciated area and contained roughly estimated an ice volume of about 3–4 % of the total glacier ice volume. The ice content of the whole permafrost area is probably much higher. Under continued warming, it can be assumed that glaciers will retreat and permafrost will degrade in Central Asia, the melting ground ice could increase future water supply, and the melt waters from permafrost could become an increasingly important source of fresh water in this region in the near future.

Introduction

High mountains have an important function as water storage and water supply for the surrounding regions. Its glaciers and ground ice are a major source of freshwater. This is especially true in arid or semi-arid areas, such as Central Asia. Therefore it is important to study their reaction to climate change.

The climate of the earth has always been characterized by natural variations. However, the mean annual air temperatures rose rather dramatically in the 20th century (IPCC 2001). This has caused increasing glacier retreat in many parts of the world (Haeberli & Beniston 1998). This trend intensified at the end of the last century and the areas of glacial ice coverage in Central Asia, like in other parts of the world, strongly diminished (Aizen et al. 2006; Bolch 2007; Khromova et al. 2003). Clearly, the permafrost also reacts to climate warming, e.g. in an acceleration of creeping of rockglaciers (Kääb et al. 2007) or a warming of the permafrost temperatures (Marchenko 1999, Vonder Mühll et al. 1998). Nevertheless, climate, glacier and permafrost changes are not homogeneous worldwide.
For example, glaciers in the more continental Pamirs retreated less in the 20th century than glaciers in the more humid parts of Tien Shan (Hagg 2003; Liu & Han 1992).

The northern Tien Shan is an ideal area to study of these changes as the climatic conditions vary within short distances and there exists a comparatively dense network of climate stations in different altitudes as well as a permanent permafrost monitoring station. The studied mountain ranges, Zailyiskiy and Kungey Alatau, a main part of the Northern Tien Shan, are situated at the border between Kazakhstan and Kyrgyzstan (Figure 1).
These mountains, which rise up to an altitude of nearly 5000 m a.s.l., are characterised by a pronounced periglacial belt with the occurrence of many active rockglaciers (ice rich creeping mountain permafrost) between 3000 and 3600 m a.s.l. The average equilibrium line altitude of the glaciers is located between 3800 and 3900 m a.s.l.

Figure 1
Location of the study area; the investigated valleys are marked (arrows); locations of selected climate stations (1 Almaty, 2 Mynzhilki, 3 Tuyuksu, 4 Novorosijka, 5 Balykchi, 6 Kyrchin, 7 Karakol) and of the permafrost monitoring Station (P) are also indicated

Methods and Data

Climate

The analysis of climate change in northern Tien Shan is based on 16 time series of temperature and precipitation (Table 1), some of them long-term. Several of them are from stations at altitudes higher than 2000 m a.s.l. and four are even located above 3000 m a.s.l. As the quality of the series was not well known, they had to be tested for inhomogeneities. This was done visually by checking the graphs and by correlation analysis, based mainly on the time series of Almaty, which was homogenized by Böhner (1996). Inhomogeneities due to false values in the time series and location shifts of the stations were detected and corrected. However, gradually occurring bias, e.g. due to increased urbanization, could not be excluded. The purpose of the correlation analysis was also to determine, whether it is possible to transfer the data from stations with longer time series to the ones with shorter time series and to find characteristic stations for areas with homogeneous trends. In doing so, the study area was divided into four parts: the northern foothills with Almaty (848 m a.s.l.) as the representative station, the mountainous areas of Zailiyskiy Alatau (Mynzhilki, 3017 m a.s.l.), the deeply incised Chon-Kemin Valley (Novorosijka, 1524 m a.s.l.) and the Issyk-Kul basin (Karakol, 1740 m a.s.l.). In addition the Bolshaja Alma Atinsjkoje Ozero station was analysed due to its close proximity to the permafrost monitoring station.

Mapping and Estimation of the Ice Content of the Glaciers and Rockglaciers

The recent glacial ice coverage was mapped using a Landsat ETM+ scene from 8.8.1999. No snow covered the glacier tongues, but a few clouds occurred in the area of the glaciers, mainly at the southern slope of Kungey Alatau. A TM4/TM5 ratio image with a threshold of two was used to delineate the glaciers. Misclassified pixels of vegetated areas and lakes were eliminated using the Normalized Difference Vegetation Index (NDVI). A similar approach was successfully utilized for the Swiss Glacier Inventory (SGI) (Paul et al. 2002). Problems arose due to moraine cover on some glacier tongues caused by the similar spectral signal of the surrounding debris. With the help of a morphometric analyses and aerial images from the year 1990 the outline of glaciers with debris parts and bigger glaciers with cloud cover in the Landsat scene could be manually delineated. An evaluation shows that the accuracy is in the order of 3 % (Bolch & Kamp 2006).

In order to quantify the glacier change this data were compared to those of the soviet glacier inventory, which represents the situation in the study area of about 1955 (USSR 1966 – 1983). However, it has to be mentioned that the glacierized areas calculated from an existing map (scale 1:10 000) of Malaya Almatinka valley from the year 1958 (Simon et al. 1961) differ more than 5 % from the glacier areas (open parts) cited

Table 1 Characteristics of the climate stations incorporated into the analyses

Nr.	Name	Location	Altitude (m a.s.l.)	Time period
1	Almaty (Alma-Ata)	Foothills	848	1879 – 2000
2	Ust-Gorelnik	Zailiyskiy Alatau	1943	1938 – 1991
3	Verchnij-Gorelnik	Zailiyskiy Alatau	2272	1970 – 1989
4	Mynzhilki	Zailiyskiy Alatau	3017	1937 – 1996
5	Tuyuksu	Zailiyskiy Alatau	3434	1972 – 1996
6	Bol. Alma Ozero	Zailiyskiy Alatau	2450	1932 – 1996
7	Assy	Zailiyskiy Alatau	2218	1952 – 1966, 1981 – 1990
8	Novorosijka	Chon-Kemin	1524	1931 – 2000
9	Kyrchin	Kungey-Alatau	2305	1980 – 1999
10	Balykchi (Rybache)	Issyk-Kul Basin	1670	1931 – 2000
11	Cholpon-Ata	Issyk-Kul Basin	1645	1929 – 2000
12	Krasnij Oktjabr	Issyk-Kul Basin	1645	1946 – 1998
13	Karakol (Prshevalsk)	Issyk-Kul Basin	1744	1879 – 1996
14	Pokrovka	Issyk-Kul Basin	1740	1951 – 2000
15	Karabatkak-Glacier	Terskey Alatau	3415	1956 – 1999
16	Tien Shan	Ak-Shiyrak	3614	1930 – 1996

Data sources: Böhner (2004), Giese (2004), published in Giese & Moβig (2004), Institute for Geography Almaty und Institute for Hydrometeorology Bishkek.

in the Soviet Glacier Inventory of this region (Vilesov & Khonin 1967). Therefore the probable maximum errors of the presented numbers of glacier retreat is about 8 %.

The outlines of the rockglaciers were drawn manually based on the mentioned Landsat scenes and aerial images as well as field investigations. The latter were also conducted to estimate the thickness of the rockglaciers.

More than 150 glaciers and more than 60 rockglaciers in six selected valleys were studied in detail using GIS and DEMs derived from SRTM, ASTER data and topographic maps. The selected valleys represent the different climatic conditions of Zailyiskiy and Kungey Alatau and were accessible by foot to obtain ground-based measurements. Unfortunately, the southern slope of Kungey Alatau could not be included in this study due to massive cloud cover in the available Landsat-ETM and ASTER scenes.

The estimation of the ice content is based on the following assumptions in table 2.

Table 2 Assumptions for estimating rockglacier and glacier ice content

Estimation of Glacier Thickness[1] [m]:	28.5 (a [km^2])$^{0.357}$
Estimation of Rockglacier Ice Content[2]	40 – 60 % by Volume
Estimation of average permafrost thickness in Rockglacier[3]	20 m

Based upon: 1 Chen & Ohmura (1990), 2 Arenson et al. (2002), Barsch (1996), Gorbunov & Severskiy, 3 Croce & Milana (2002), Gorbunov & Titkov (1989), own investigations

Permafrost – temperatures, distribution and ice content

The initial investigations of mountain permafrost in the Tien Shan began in the mid-1950s (Gorbunov 1967, 1970). General features of permafrost distribution in the Tien Shan Mountains are resulting from latitudinal and altitudinal zonality, and from changes in climatic and topographic factors. The regional patterns of permafrost distribution depend on elevation, slope, and aspect, which have a major influence on incoming short-wave radiation to the ground surface. Vegetation and snow cover, ground texture and moisture content, winter air temperature inversion, surface and groundwater presence and movement, and climatic and geothermal conditions are also among the most important parameters shaping the mountain permafrost distribution.

Coarse blocky debris of various origins is widespread in the Tien Shan and occupies a large area of high-mountain territory. Convective mass and heat transfer, especially during the cold period, are very typical for the blocky material because of its high porosity. The measurements in the Zailiysky Alatau Range during 1974–87 show that the temperatures inside the coarse debris are typically 2.5–4.0 °C colder than the mean annual air temperature (MAAT) (Gorbunov et al. 2004). For this reason the altitudinal distribution of rockglaciers are a few hundreds meters lower than that of open glaciers.

In mapping of mountain permafrost distribution in Tien Shan, the traditional approach has been based on the dividing of mountain ranges into sub-belts of different types of permafrost distribution (Gorbunov 1986). Within the overall permafrost belt in the Northern Tien Shan, sub-belts of sporadic (2700–3200 m a.s.l.), discontinuous (3200–3500 m a.s.l.), and continuous (3500 m a.s.l. and higher) permafrost have been identified (Gorbunov 1986; Gorbunov et al. 1996). The total area of permafrost within each of these sub-belts is: sporadic – not more than 30 %, discontinuous – not more than 70 %, continuous – not less than 90 %. However, small isolated patches of permafrost can be found much lower than 2700 m a.s.l. These patches occur at the feet of north-facing or shaded slopes inside the coarse blocky debris or beneath a mossy cover even at 1800 m a.s.l. where the MAAT is 3.0–4.0 °C (Gorbunov 1993).

An alternative approach for the mapping of mountain permafrost is the modeling of ground temperature and permafrost distribution using process-based models (Marchenko 2001, 2006). Such an approach allows for a spatial and temporal extrapolation of the permafrost thermal state and distribution and is also well suited for studies of the permafrost response to climate change. But process-based models require an extensive set of input data such as meteorological data, surface characteristics (vegetation, snow cover), ground thermal properties, and topography.

For the modeling of altitudinal permafrost within rugged topography, the basic data set is a digital elevation model (DEM). The grid-based map of meteorological variables could be used as input data.

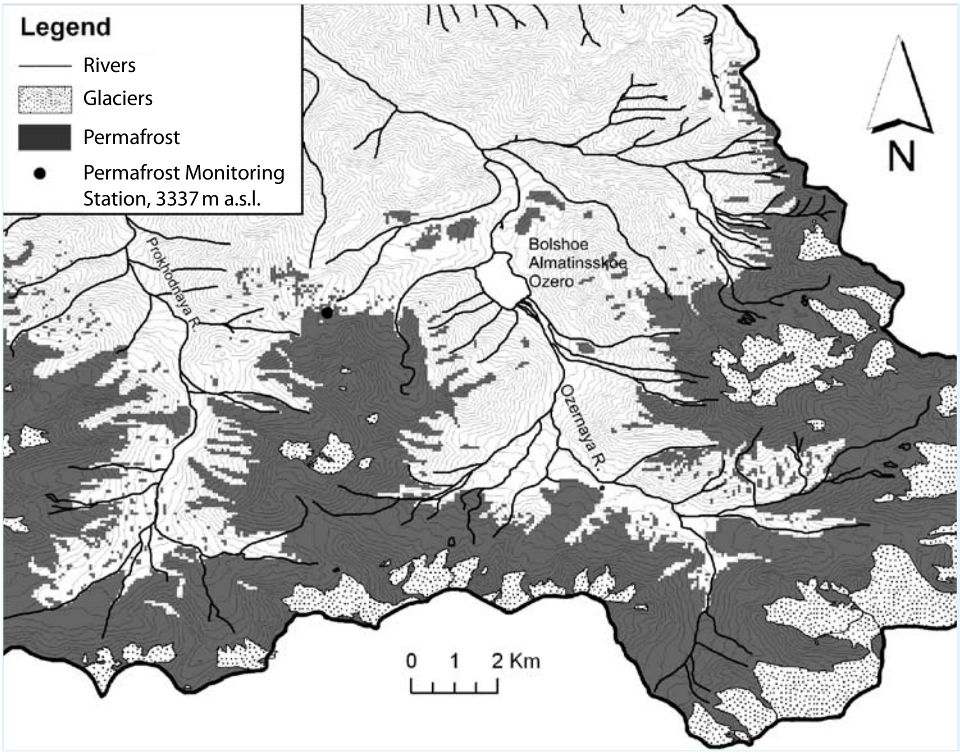

Figure 2
Fragment of the modeled map of permafrost distribution within the Bolshaya Almatinka River basin.

The investigated area was overlaid with a grid (250 × 250 m). The calculation of the ground temperature regime for each grid point was accomplished with an external program module, which can be called from the GIS. One result of the calculation is a database file containing the ground temperatures for each grid point. Because the goal of the calculations was to assess the permafrost extent, the mean annual ground temperature (MAGT) at 20 meters depth was selected as an output. This information was transferred back into the GIS using interpolation methods and producing a grid with a cell size of 100 × 100 m (Figure 2).

The mean annual temperature at the permafrost table and the heat flux at the bottom are the main thermal characteristics of permafrost. These parameters are very important not only for estimating the distribution and thickness of permafrost, but also for the evaluation of the sensitivity of permafrost to climate change and to natural or human-induced disturbances. The first systematic permafrost temperature measurements in the Northern Tien Shan began in 1973 (Gorbunov & Nemov 1978). One of the permafrost research stations of the Russian Academy of Sciences was established at 2500 m a.s.l. in 1974. The area of original permafrost studies in the Northern Tien Shan is located within the Bolshaya Almatinka river basin within the altitude range between 2000 and 3500 m a.s.l. During the last 30 years, staff members of the Kazakh Alpine Permafrost Laboratory, which belongs to the Yakutsk Permafrost Institute, conducted permafrost investigations. A variety of methods, including measurements of permafrost temperature, the active layer thermal regime and thickness, spring water temperatures, and DC resistivity soundings were used (Gorbunov & Nemov 1978; Zeng et al. 1993; Gorbunov et al. 1996).

There are 21 active thermometric boreholes with depths ranging from 2.2 m to 300 m in different landscape settings and at varying altitudes (2500 – 3330 m a.s.l) available for measurements in this region near the two permafrost stations in the Zailiysky Alatau. Ground temperature measurements are carried out by using thermistor sensors (MMT-4 and TSM-50) with a sensitivity 0.02 °C and an accuracy of not less than 0.05 °C. There are five sites equipped with temperature data loggers (StowAway Onset Computer Corporation) that have been in operation since 1997. These sites were established as a contribution to the IPA Circumpolar Arctic Layer Monitoring (CALM) project. Data from these sites are regularly added to the CALM site database. A few deep boreholes in the Northern Tien Shan belong to the Global Terrestrial Network of Permafrost (GTNet-P) Program (Burgess et al. 2001).

Initial geothermal observations (1974 – 1977) in boreholes in the northern Tien Shan showed that the permafrost temperatures within the loose deposits and bedrock at the altitude of 3300 m a.s.l vary from –0.3 °C to –0.8 °C (Gorbunov & Nemov 1978). Thickness of permafrost in this area varied from 15 to 90 m and the maximum active layer thickness reached 3.5 – 4.0 m.

Mountain permafrost and associated periglacial landforms contain large quantities of stored fresh water in the form of ice. The lacustrine and sometimes alluvial sediments, moraines, rockglaciers and other coarse blocky material have especially high ice content (20 – 80 % by volume). During the deep excavations (down to 12 m) in the in the Late Pleistocene and Holocene moraines, near one of the permafrost research stations (3336 m a.s.l), massive, syngenetic cryogenic formations with 15 – 20 cm thick ice lenses were revealed at depths below 4.0 – 4.5 m. The measured excess ice content in these formations amounts to 10 % to 40 % by volume (Gorbunov & Nemov 1978). These cryogenic formations can be treated as proof that permafrost has continuously been in existence here during the entire postglacial time.

According to Gorbunov & Severskiy (1998) the total volume of ground ice in the Northern Tien Shan is about 56 km³ which equals 62 % of the surface ice volume for the same territory. The estimated ground ice volume for the Bolshaya Almatinka river basin is about 0.6 km³ or 87 % of the surface ice volume in the basin (Gorbunov & Severskiy 1998). It should be noted that this assessment was performed for the whole permafrost area in the region. Frozen ground within the permafrost area was classified as bedrock (1 % ice content), coarse debris filled with fine-grained soils (ice content 20 %), and coarse debris unfilled with fine-grained soils (ice content 50 %). This approximate evaluation shows that the quantity of water stored as a ground ice in the Tien Shan is comparable to the volume of modern glaciers in the same region.

Recent Climate Changes

All trend coefficients of MAAT for the time period from 1950 to 1996 (Table 3) are positive. Almaty and Karakol, two stations not situated in the high mountain area, have higher positive trends than the high mountain stations, Mynzhilki and Tien Shan, and the valley station Novorosijka. Analyzing all available stations, it could be stated that there is a decreasing trend with altitude, but the trend is still positive in the high altitudes of Zailiyskiy and Kungey Alatau. Giese & Moßig (2004) even found a negative trend in high altitudes for Central Asia.

A more detailed analysis of the temperature development showed that the increase in the MAAT was, for the majority of the high mountain mountain stations above 2000 m a.s.l., caused by the strong rise of the temperatures in autumn, whereas the temperature increases of the summer half-year were less pronounced (Table 3). In contrast, the summer temperature rise at the Tien Shan station, situated in central part of Tien Shan was more pronounced than the autumn and winter air temperature rise.

Table 3 Trend coefficients for the yearly and seasonally air temperature change of the time period 1950 – 1996

Station	Alt. [m a.s.l.]	Trend coefficients [K/100a]				
		Year	MAM	JJA	SON	DJF
Almaty	848	2.37	+1.12	+0.68	**+2.53**	+2.03
Atinsk. Oz.	2516	0.57	–1.25	+1.03	**+1.86**	-0.23
Mynzhilki	3017	2.04	+1.97	+3.22	**+3.54**	+1.63
Novorosijka	1524	1.16	–0.16	+1.16	**+3.49**	+2.29
Karakol	1718	2.66	+1.6	+2.65	**+3.25**	+3,34
Tien Shan	3614	0.8	–0,26	**+1,54**	+1,27	+0.23

Two facts should be mentioned regarding the air temperature trends (Figure 3). First, the stations at the foothills are located mostly in the area of larger settlements and therefore, the higher air temperature increase could certainly be at least in part due to an increased urbanization of the surroundings. Second, the choice of the beginning and end times for the calculation of the air temperature trend coefficients has a considerable influence on the value. For this study, they were chosen on the basis of the availability of the data, and in such a way that the trends are clearly visible but not unrealistically exaggerated.

It is well known that the variation in precipitation is spatially and temporally much higher than the variation in temperature. A homogeneous trend in precipitation, as was obtained for temperatures, could not be detected. Since the 1950s at the latest, precipitation has risen slightly at the stations below 2000 m a.s.l., whereas it has decreased at the high mountain stations since the middle of the 1960s. The trends were similar in summer and winter. In recent times these trends seemed to reverse; thus it cannot be stated that there is a general change in precipitation conditions.

Glaciers and Glacier Changes Since 1955

In the six investigated valleys, three glaciers advanced, seven had more or less the same size while a particularly strong area loss could be measured from about 1955 until 1999 at all the other glaciers. The glacier extent diminished, on average, by about 32.6 ± 8 % in area (from ~247 to ~164 km²).

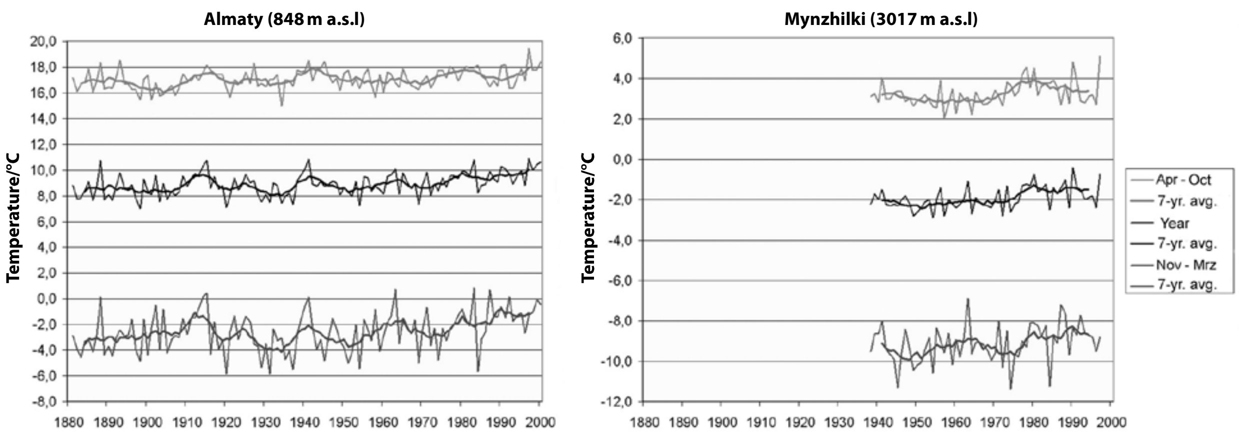

Figure 3 *Time Series of yearly air temperature and the temperatures of the summer-and the winter half year for the stations Almaty and Mynzhilky located in Zailiyskiy Alatau (Nr. 1 and 2 in Figure 1).*

The estimated volume of glaciers diminished from ~10.7 to ~6.7 km³ (~37.5 ± 9 %). However, the individual glacier retreat varied strongly (from –16 % to –38 % in area) depending on size, location, and climate conditions. In general, larger glaciers react more slowly to a modification of the climate and glaciers in more maritime climates are retreating more than those located in more continental climates. However, radiation and precipitation also clearly have a high impact (Bolch 2006, 2007). These results are similar to those obtained by Vilesov & Uvarov (2001), who found a change of 29.2 % in glacier area and 32.2 % in glacier volume on the northern slopes of Zailiyskiy Alatau from 1955 to 1990.Analyzing the time periods 1955 – 1979, 1979 – 1990 and 1990 – 1999 shows that the retreat rate was highest between 1979 and 1990 (Bolch 2006, Table 4). The glacier recession in the high continental areas of Tien Shan, such as the Terskej Alatau or the Ak-Shirak range in Inner Tien Shan is less pronounced (Aizen et al. 2006; Narama et al. 2006).

Rockglaciers and Permafrost

Rockglaciers are the clearly visible form of mountain permafrost and they are widespread in Northern Tien Shan. Figure 4 shows the occurrence of these creeping permafrost bodies as well as the glaciers in three investigates valleys at the northern slope of Zailyiskiy Alatau.

More than 60 active rockglaciers cover an area of about 21.4 km² (ca. 13 % of the glaciated area) in the investigated valleys. However, the occurrence of the rockglaciers is variable in the study area. The rockglacier coverage varies from less than 1 % of the area above 3000 m a.s.l. in Turgen valley to nearly 5 % in the Bolshaja Almatinka valley (Table 5). Detailed investigations of the rockglacier density can be found also in Gorbunov & Titkov (1989) and Kokarev et al. (1997).

The active rockglaciers contain, roughly estimated, an ice volume of more than 0.2 km³, which is on average more than 3 – 4 % of the glacier volume. Whereas the ice volume of the rockglaciers in Turgen valley is only about 1.5 %, it approximates 10 % in Bolshaja Almatinka valley, where most of the water supply for the million city Almaty originates from (Table 6).

The water storage of the rockglaciers compared to the glaciers in Northern Tien Shan is about two to three times higher than in the Alps, where it was estimated to be 1,2 to 1,5 % (Barsch 1977), but lower than in the Central Andes of Chile, where the water storage was estimated to be bigger than 10 % (Brenning 2005).

Recent studies show an acceleration of rockglacier movement throughout the Alps, which is probably mainly caused by the temperature rise (Kääb et al. 2007).

Table 4 Area changes of the glaciers in the investigated valleys for different time periods; based on Bolch (2006), Cherkassov et al. (2002), USSR Akademia Nauk (1966 – 1983) and Soviet topographic maps. The probable error of the numbers is about 8 %

Investigated Valley	Area change 1955 – 1999		Area change 1955 – 1979		Area change 1979 – 1990		Area change 1990 – 1999	
	Rel. [%]	Rate [%/a]	Rel. [%]	Rate [%/a]	Rel. [%]	Rate [%/a]	Rel. [%]	Rate [%/a]
Malaya Almatinka	–37.6	–0.85	–13.2	–0.69	–22.8	–1.42	–6.9	–0.77
Bolsh-Almatinka	–34.5	–0.78	–17.5	–0.92	–15.9	–0.99	–5.7	–0.63
Levyj Talgar	–33.6	–0.76	–15.1	–0.76	–20.8	–1.30	–1.2	–0.14
Turgen	–36.5	–0.83	–17.4	–0.92	–15.0	–0.94	–9.5	–1.06
Average	**–34.5**	**–0.78**	**–16.5**	**–0.69**	**–18.0**	**–1.64**	**–4.5**	**–0.48**
	Area change 1955 – 1999		**Area change 1955 – 1979**		**Area change 1979 – 1999**			
	Rel. [%]	Rate [%/a]	Rel. [%]	Rate [%/a]	Rel. [%]	Rate [%/a]		
Chon Aksu	-38.2	-0.87	-29.9	-1.25	-11.8	-0.59		
Upper Chon Kemin	-16.4	-0.37	-9.3	-0.46	-7.8	-0.32		
Average all	**32.6**	**-0.74**	**-18.5**	**-0.77**	**-17.3**	**-0.86**		

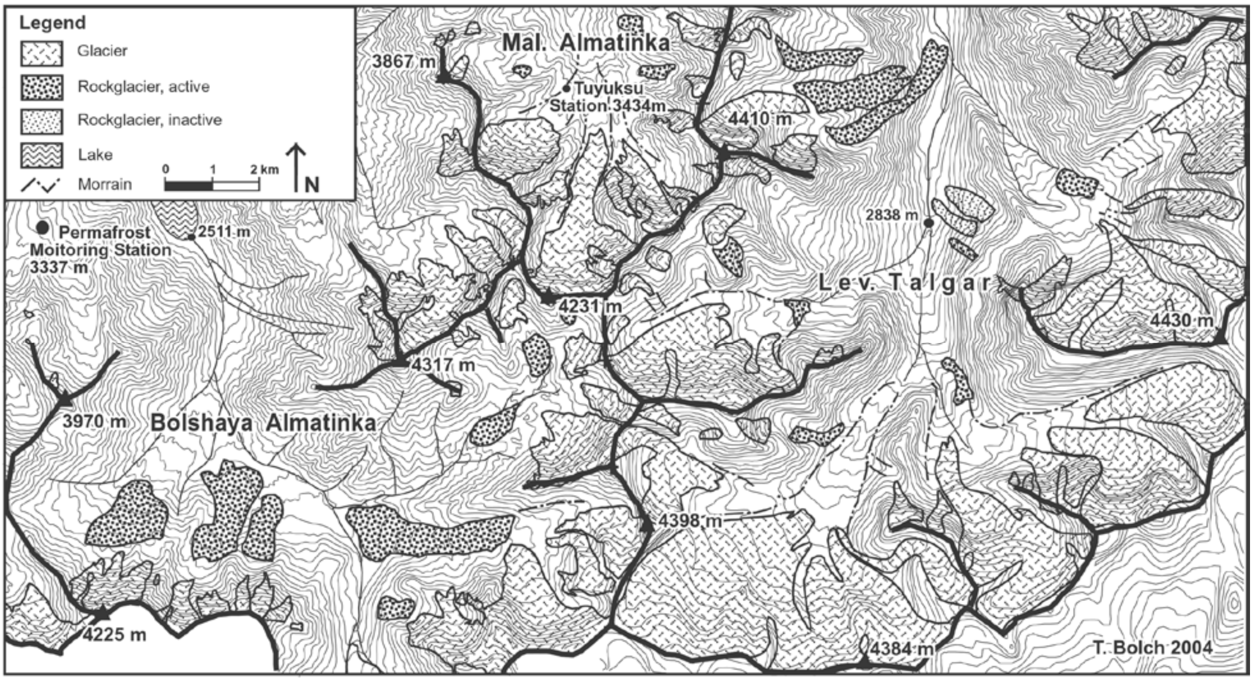

Figure 4 *Location of the permafrost monitoring station and the Tuyuksu glacier station as well as locations of the glaciers and rockglaciers in the valleys Bolshaya, Malaya Almatinka, and Levyj Talgar.*

Table 5 Comparison of the area of glaciers and rockglaciers

Investigated Valley	Area of Glaciers	Portion of Study Area > 3000 m a.s.l.	Area of active Rockglaciers	Portion of Study Area > 3000 m a.s.l.	Rockglaciers/ Glaciers
Bolshaja Almatinka	16.45 km^2	16.3 %	4.77 km^2	4.7 %	0.29
Malaja Almatinka	5.79 km^2	15.4 %	0.47 km^2	1.2 %	0.09
Levij Talgar	48.35 km^2	29.4 %	5.58 km^2	3.4 %	0.12
Turgen	22.98 km^2	13.5 %	1.16 km^2	0.7 %	0.05
Chon-Aksu	38.62 km^2	16.3 %	6.22 km^2	2.6 %	0.16
Upper Chon-Kemin	32.2 km^2	15.4 %	3.2 km^2	3.2 %	0.10
Sum or Average	164.39 km^2	20.0 %	21.4 km^2	2.65 %	0.13

Table 6 Estimated ice volume of the glaciers and rockglaciers

Investigated Valley	Glacier Ice Volume	Rockglacier Ice Volume	Rockglacier/ Glacier Ice
Bolshaya Almatinka	0.51 km^2	0.048 km^2	9.4 %
Malaya Almatinka	0.18 km^2	0.005 km^2	2.6 %
Levij Talgar	2.23 km^2	0.056 km^2	2.5 %
Turgen	0.88 km^2	0.012 km^2	1.3 %
Chon-Aksu	1.48 km^2	0.062 km^2	4.2 %
Upper Chon-Kemin	1.39 km^2	0.032 km^2	2.3 %
Sum or Average	6.67 km^2	0.214 km^2	3.2 %

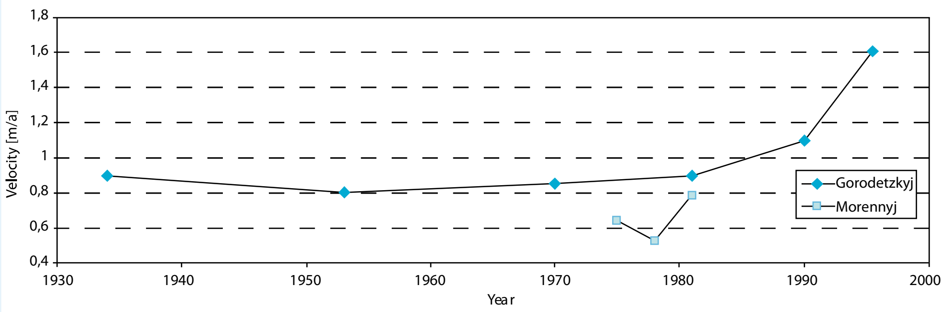

Figure 5
Rate of movement of the frontal lobe of the rockglaciers Gorodetzkij and Morennij; based on Gorbunov et al. *(1992) and Marchenko (2003).*

Measurements of the movement of the rockglaciers in Northern Tien Shan also showed a tendency to speed up (Gorbunov & Titkov 1989; Gorbunov et al. 1992). A long time series of front variation measurements exists for the rockglacier Gorodetzkij (1923–2003, Marchenko 2003). An analysis of this time series also showed an acceleration of the rockglacier movement (Figure 5).

Geothermal observations during 1974–1977 and 1990–2005 indicate that permafrost has been warming in the Tien Shan Mountains during the last 30 years. The increase in permafrost temperatures in the northern Tien Shan during 1974–2005 varies from 0.3 °C to 0.6 °C . In accordance with interpolation of borehole temperature data, the active-layer thickness (the layer of ground subject to annual thawing and freezing in areas underlain by permafrost) showed an increase during the last 30 years from 3.2–3.4 m in the 1970s to a maximum of 5.2 m in 1992 and to 5.0 m in 2001 and 2004 (Figure 6). The average active layer thickness for all measured sites increased by 23 % in comparison to the early 1970s.

As a result of a deep ground thawing, a residual thaw layer (talik) between 5 and 8 m in depth has appeared at several sites (Figure 6, b).

Modeling of the permafrost thermal state (Marchenko et al. 2007) indicates significant changes in permafrost temperature and extent during the 20th century in the Tien Shan Mountains. The main objectives of the modeling process were to estimate the permafrost thermal regime and to assess the area where permafrost has disappeared during the second part of the nineteenth century.

The results of numerical simulations show that the permafrost area within the altitudinal range of 2500–2700 m a.s.l. was about 20 % larger during the middle of the Nineteenth century compared to the present. Near the lower altitudinal boundary of permafrost distribution the permafrost temperatures now are close to 0 °C and at some sites permafrost degradation has already started. Analysis of measured active layer and permafrost temperatures coupled with numerical thermal modeling (permafrost temperature reanalysis) shows that most of the recently thawed permafrost was formed during the Little Ice Age. The modeling of alpine permafrost dynamics shows that the altitudinal lower boundary of permafrost distribution has shifted upward by about 150 m since the end of the Little Ice Age (circa 1850). During the same period, the area of permafrost distribution within the Northern Tien Shan decreased by approximately 16 % (Marchenko et al. 2007).

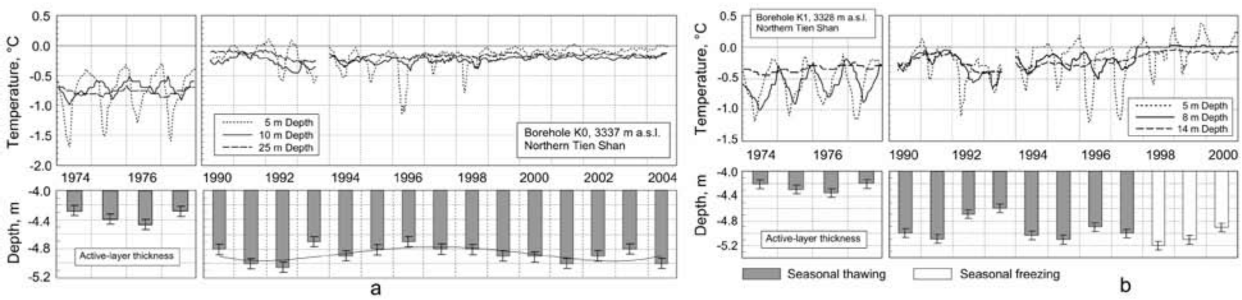

Figure 6 *Permafrost temperatures and active-layer thickness variations during 1974-1977 and 1990-2004 measured in two boreholes at the permafrost monitoring station (the location of this observatory is shown in figs. 1 and 2).*

Discussion and Conlusion

Glaciers are, in comparison to permafrost, more sensitive components of the cryosphere, reacting rapidly to climate changes. This reaction is reflected in the shrinkage of the glaciated area, the decrease of glacier volume and an increase of glacier runoff. Due to possible continued warming, glaciers will probably retreat to the highest elevation, lose some of their volume, and some of them will disappear completely and will contribute much less melt water to a river runoff. Permafrost, as a more conservative component of the cryosphere, could remain in a relatively more stable state than glaciers. While the increase in permafrost temperature may change many of its physical properties, a major shift will occur when permafrost starts to thaw from its top down. The most significant impacts on permafrost thermal state will be observed near the lower boundary of the alpine permafrost distribution; the region where the frozen ground is very sensitive to changes in surface energy balance.

Thawing and degradation of ice-rich permafrost could provide additional amounts of melt water to river runoff. In the high-mountain regions, the further near-surface permafrost degradation will probably be accompanied by a transformation in environmental conditions and may lead to slope instability and permafrost-related hazards such as landslides, thermokarst, and mudflows.

Our estimation of ground ice volume in the Northern Tien Shan Mountains was limited to rockglaciers and did not take other forms of ground ice within the permafrost area into consideration, similar to the estimation described by Gorbunov & Seversky (1998). It is possible that our rough assessment of rockglacier ice content somewhat underestimates the real values. No special investigations of the internal structure of rockglaciers and its ice content were carried out in the Northern Tien Shan so far. Our recent investigations demonstrated the presence of a significant amount of layered ice in the frontal part of rockglaciers. Several sections of buried ice with a total thickness up to 8–10 m were found in the front scarps of rockglaciers at an elevation of 3100 m a.s.l. Crystal structure and bubble shapes in the ice are similar to those found in glacier ice. These findings allow us the rough estimation of some morphologic type (near ice) of rockglaciers with ice contents of up to 80 % of the entire volume of these cryogenic landforms.

Future research focusing on the estimation of the contribution of permafrost and ground ice depletion to river runoff will make it possible to define the proportion of each runoff component (liquid/solid precipitation, glaciers and permafrost) in the total river runoff more precisely. In order to make these estimates, we need to seek explanations of the physical processes and mechanisms controlling these phenomena.
The assessment of ground ice volume and its role in freshwater runoff will allow the establishment of a predictive estimation of river runoff in accordance with regional scenarios of climate change in the Tien Shan.

Established relationships between recent climate change, glaciers retreat, permafrost warming and degradation, and changes in surface water runoff in the high-altitude Central Asia region will make it possible to predict the potential volume of ground ice that could be involved in the actual contribution to fresh water runoff. When coupled with obtained hydrologic data, a spatially distributed thermal model (Marchenko 2001) will provide essentially new information on the impact of climate warming on regional hydrology. This knowledge will facilitate climate change detection, climate impact assessments, planning for adaptation to climate and its extremes and will, in addition, support many socio-economic and environmental applications especially in fields such as land use planning and water resources management.

It can be assumed that under continued warming, the glaciers of Central Asia will retreat and the permafrost will degrade. Water from the melted ground ice could increase future water supply, and the melt waters from permafrost regions could become an increasingly important source of fresh water in this region in the near future. This is especially true for the summer months, when the need for water is highest due to irrigation.

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